High Voltage Converter / Modulator

NC (warm linac):

- Drive 1 ea. 5 MW or 2 ea. 2.5 MW klystrons or 3 ea. 2.5 MW klystrons (reduced power)
  - 5 MW / 0.45 = 11.1 MW peak @ 140 kV
  - 2 × (2.5 MW / 0.55) = 9.1 MW peak @ 130 kV
  - 11 MW peak for 3 2.5 MW klystrons

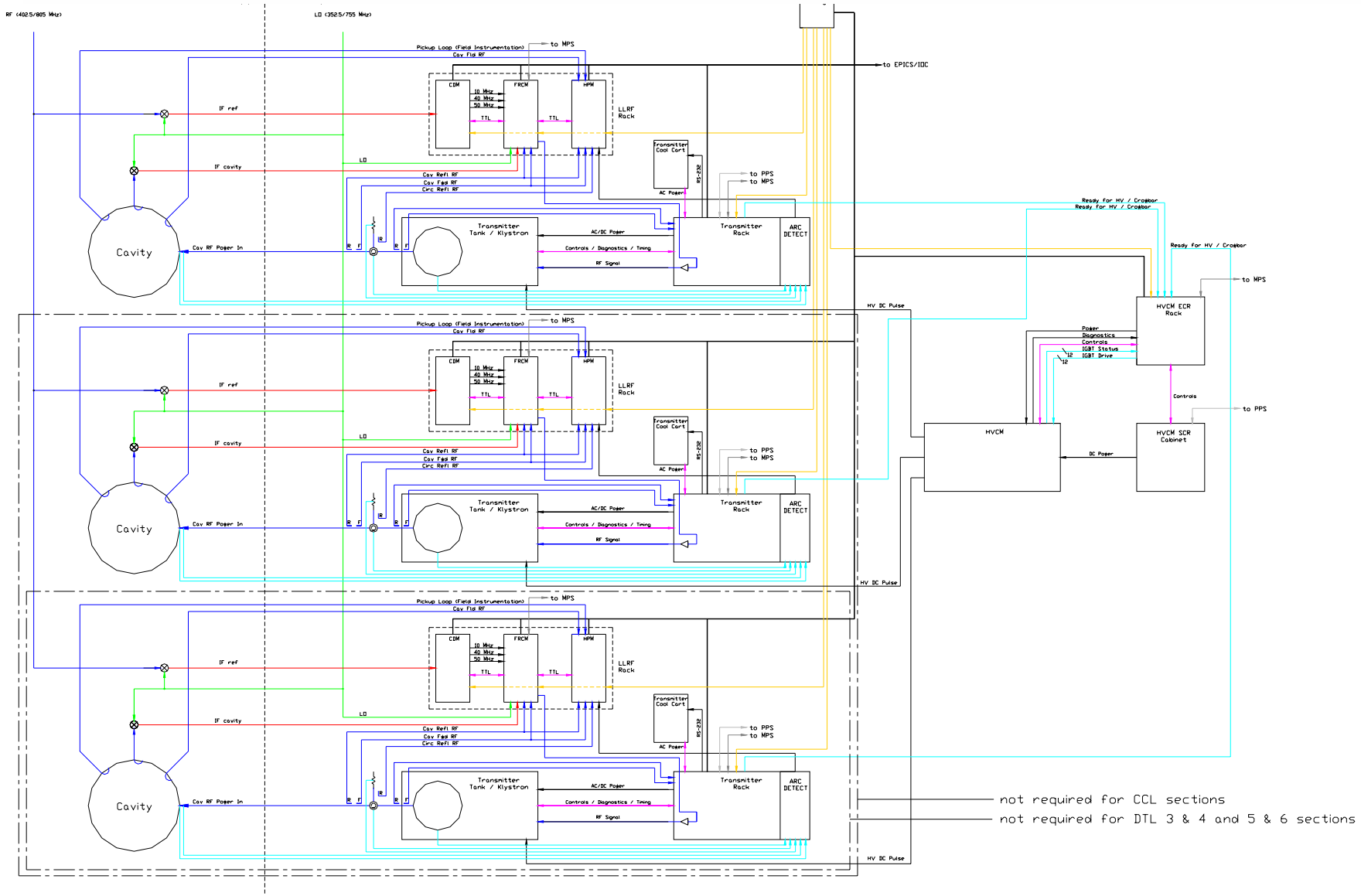
SC (superconducting linac):

- Drive 11 ea. 550 kW klystrons (full power) or 12 ea. 550 kW klystrons (reduced power) @ 69 kV
  - 550 kW / 0.63 = 870 kW

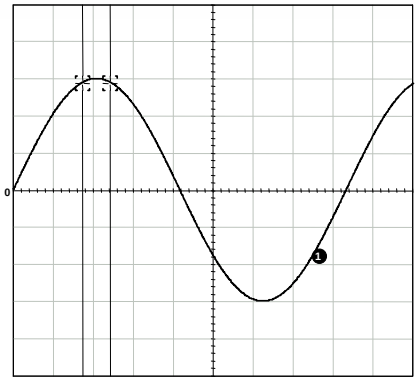
All linac:

- 1.4 ms pulse width (allows for cavity fill, modulator risetime, LLRF stabilization period)
- ±½% voltage flattop required (⇒ ±½° phase stability)
- Efficiency ≥85% (⇒ 165 kW of heat generated)

RF Block Diagram



Power Conversion Options



- Use “stepped-up” raw sine wave?
  - ⇨Flat to ±3.5% over 1.4 ms
  - ⇨Would require 4.6 MW for 805 MHz NC klystron (5X wasted power)

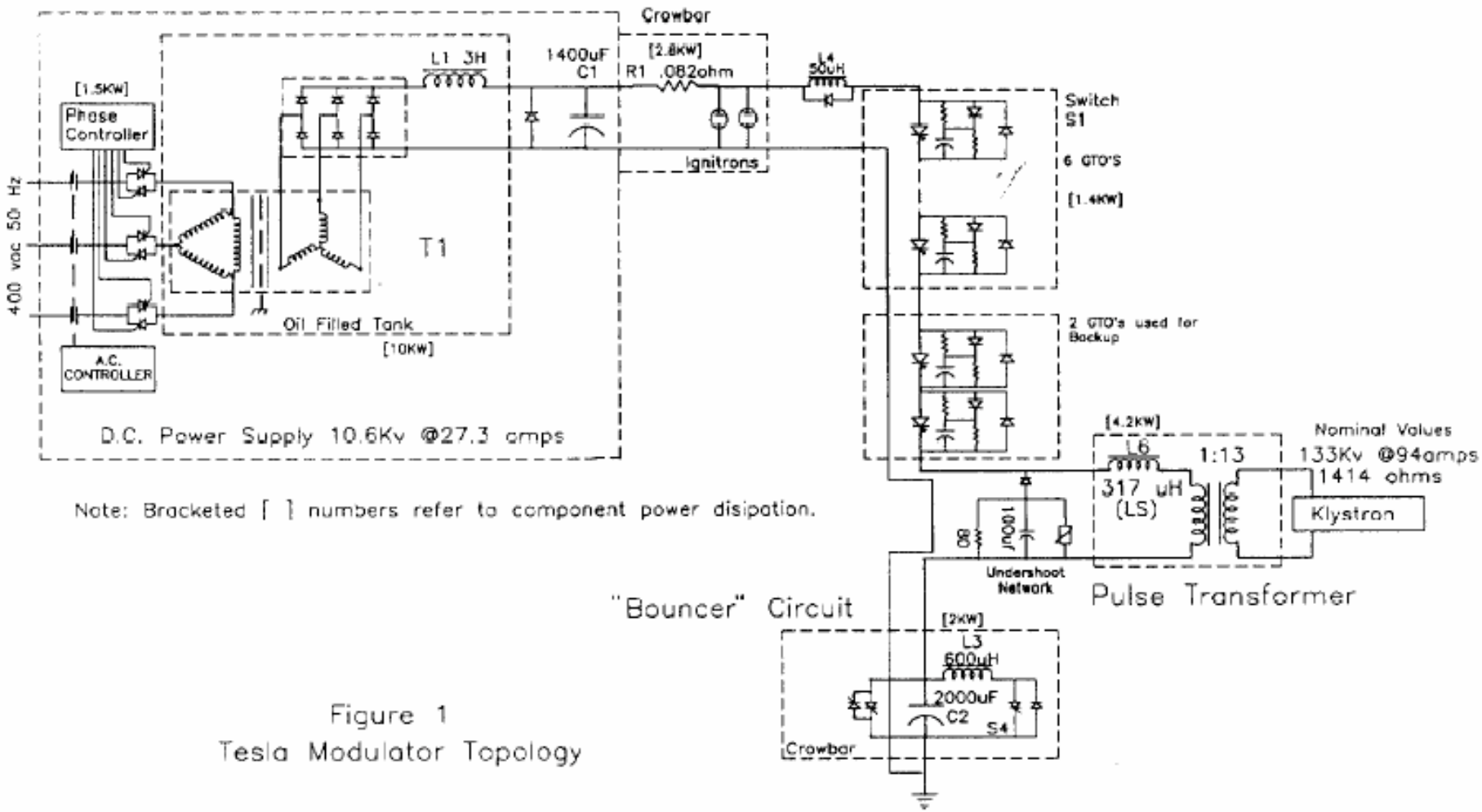
- Traditional “hard tube” modulator approach?
  - ⇨Large capacitor bank with high-voltage series switch
  - ⇨130 μF required to keep droop at ≤½% = 1.3 MJ at 140 kV (3 sticks TNT)
  - ⇨Requires ~25’ × 25’ × 8’ for capacitors alone

- PFN/Transformer?
  - ⇨Fixed pulse width, variable involves more switching
  - ⇨Fast switching required at moderate voltages
  - ⇨Large ∫ Vdt transformer for >1 ms pulsewidth

Existing IGBT Modulators

- DTI Modulator
  - Utilizes Series IGBTs to switch HV
  - No regulation possible
  - Requires complex voltage distribution and protection
- Tesla Modulator
  - 1st use of IGBTs in HV application
  - Uses series switches and pulse transformer
  - Suffers from complex voltage distribution, multiple switches, and large HV pulse transformer

Existing IGBT Modulators -- TESLA

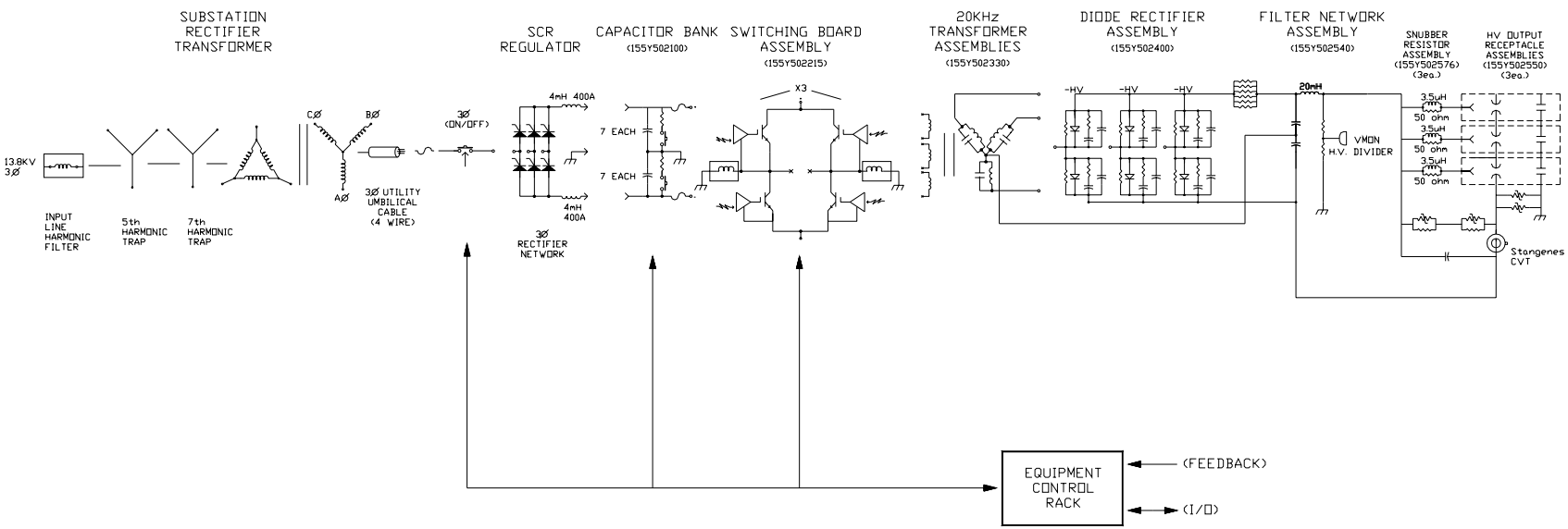


Note: Bracketed [ ] numbers refer to component power disipation.

Figure 1
Tesla Modulator Topology

Simplified Block Diagram

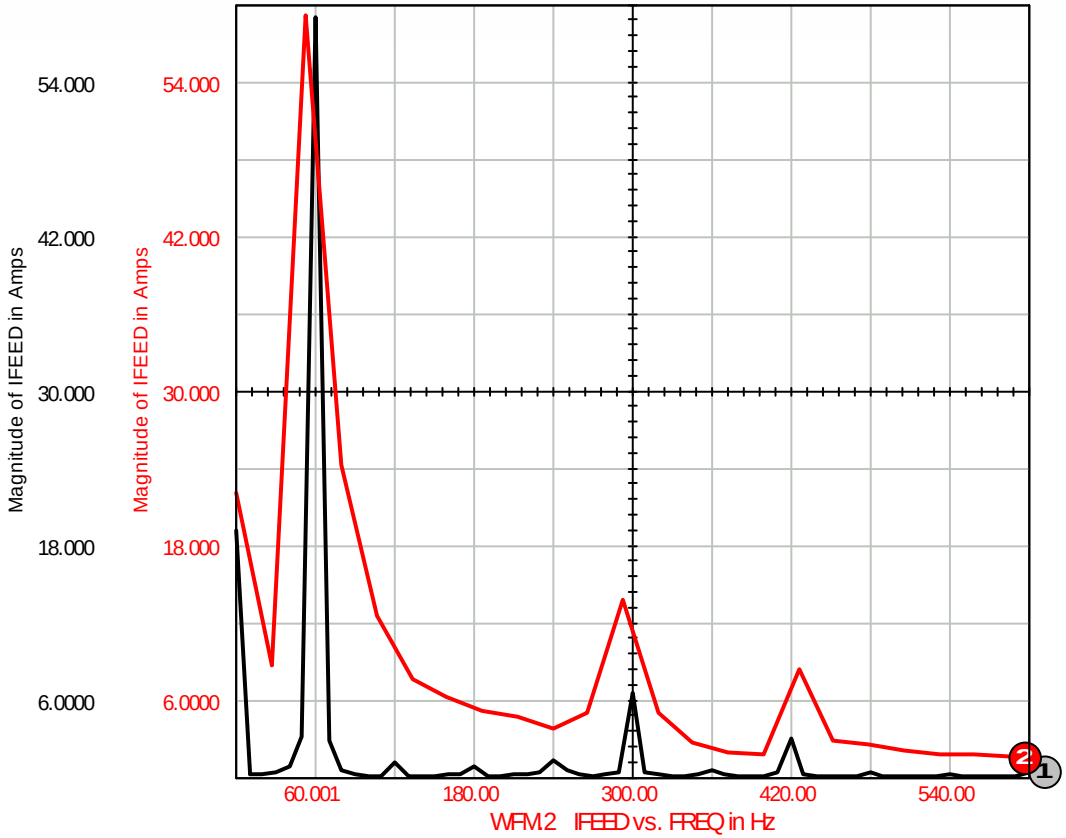
- Design which utilizes high frequency switching capabilities of IGBTs
- Minimizes # of series IGBTs in switching sections
- Significantly reduces size of pulse transformer



AC Power Management

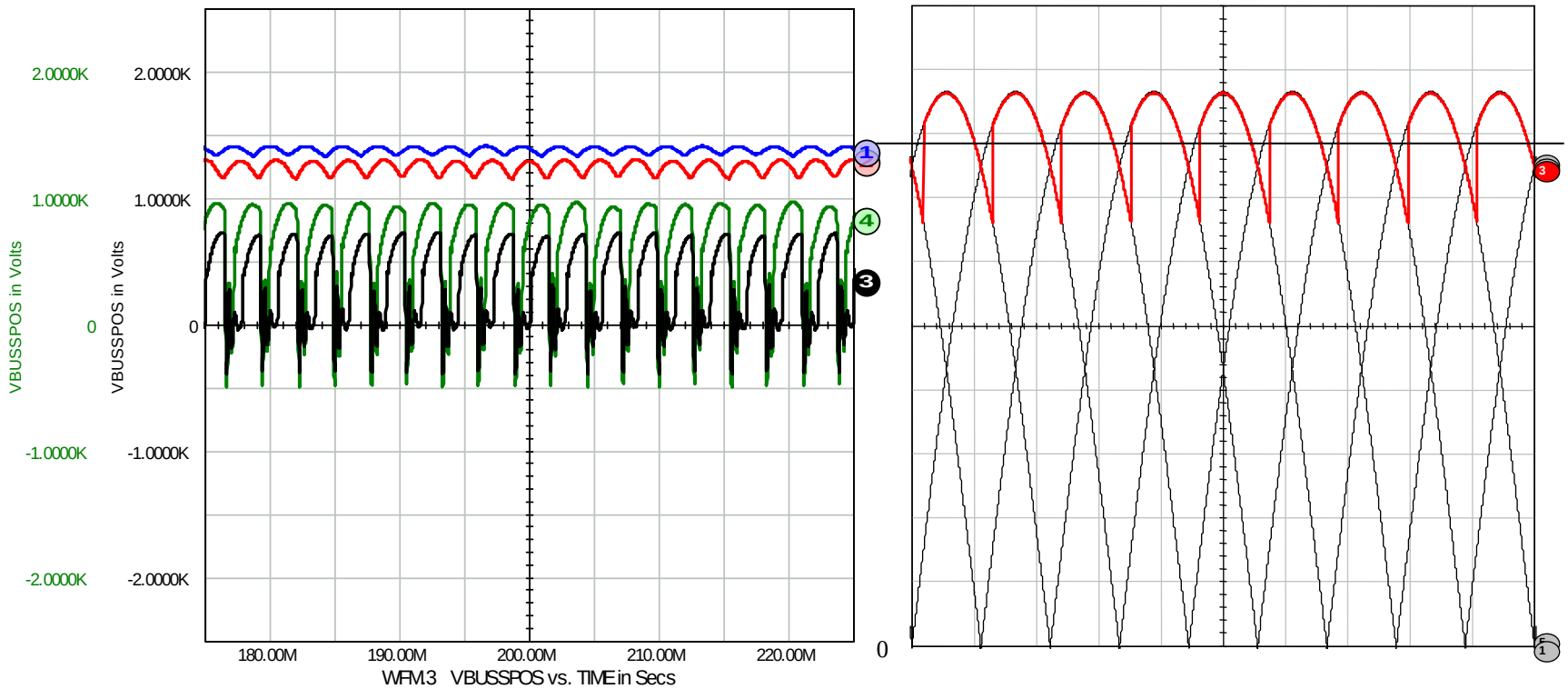
- Use industry standard 13.8 kV : 2100 V 1.5 MVA transformer
  - ⇨2100 Vac distribution into bldg. straightforward
  - ⇨±1250 V peak allows rectification with single device
  - ⇨3 phase system minimizes ripple and maximizes power delivered
  - ⇨Dry type transformer eliminates environmental concerns, need for secondary oil confinement

“Traps” Eliminate Harmonics



- 5th and 7th Harmonic Traps in Transformer
- Reduces harmonics by 2.3

3 phase SCR Controller Voltage



- Converts low voltage AC power into DC power
- Allows for “coarse” adjustment of voltage levels by varying conduction angles (shorter≡higher voltage)
- Provides “knob” for DC voltage regulation
- Limits “in-rush” current at turn-on

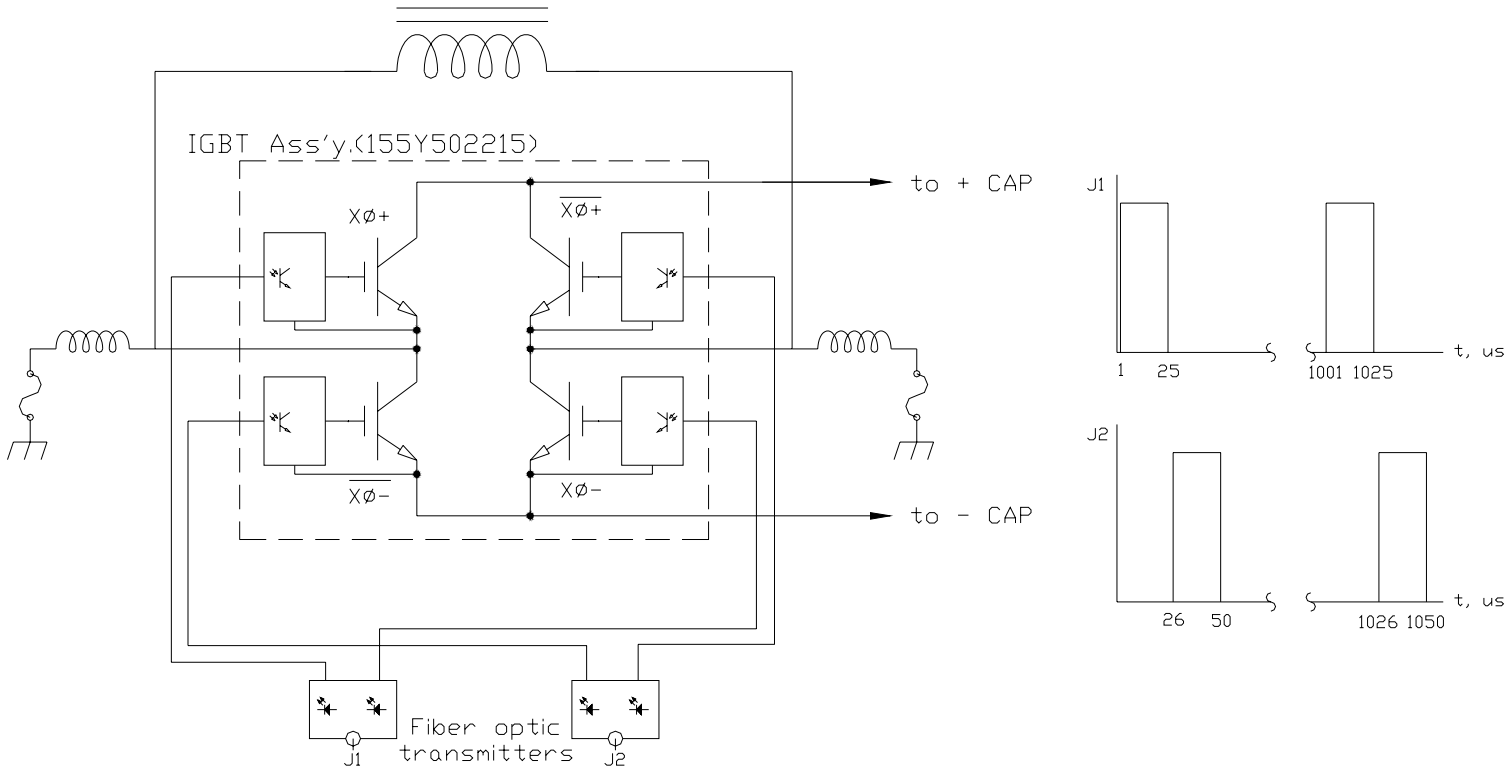
Storage Capacitors & IGBT switches

- Self-clearing design protects hard-bussed units
- 110,000 μF per polarity is 160 kJ stored energy
- 20 years in service in traction motor industry w/o failure

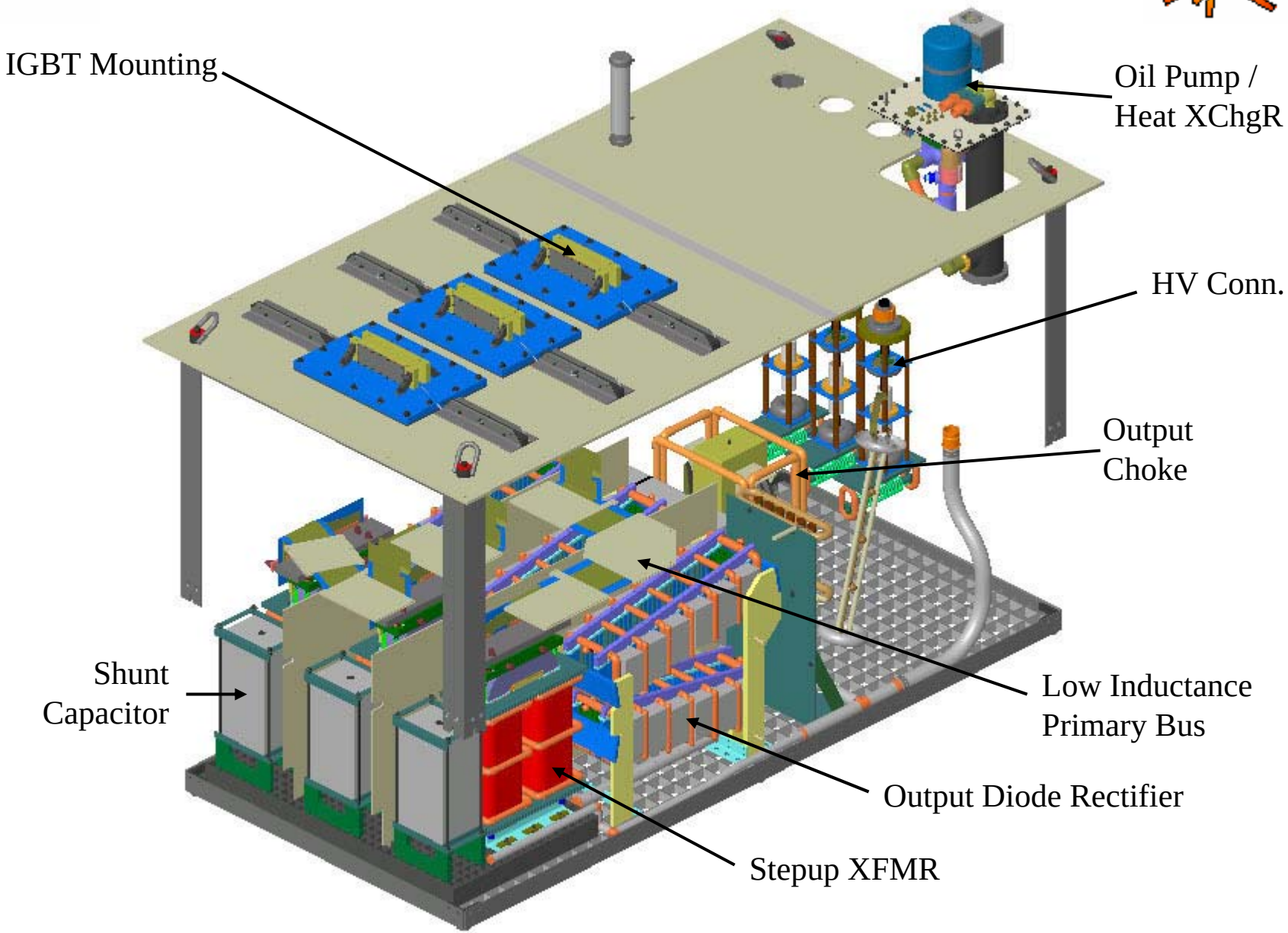
- Tradeoff between switching frequency (lower = smaller switching losses) and size of magnetics (lower = larger magnetics)
- 20 kHz H-bridge in 3 phases
- Pulse-width modulated

IGBT H-bridge

- Bipolar switching to simplify magnetics design
- Pulse Width Modulation (PWM) to control output voltage level and regulate output waveform
- 20 kHz operation results in switching losses (~5 kW/device)



Tank Basket Assembly



Boost Transformer / DC Rectifier

- 1:18 high voltage stepup transformer
  - ⇨World's largest amorphous nanocrystalline cores
  - ⇨~300 W / pulse loss, order of magnitude below Metglas
  - ⇨Combined with triple-resonant filter circuit to produce 1:47 voltage gain required for 140 kV pulses
- Series HV diodes for DC rectification
- Output filter <20 J of stored energy (minimizes damage from arcing klystrons) – 1 J measured @ 93 kV ⇒ 2.25 J @ 140 kV

Equipment Control Rack

Switchgear Remote Operator – keyed switch allows for remote open/close

SCR Control Head – not used for remote operation (displays active)

Power Distribution Panel

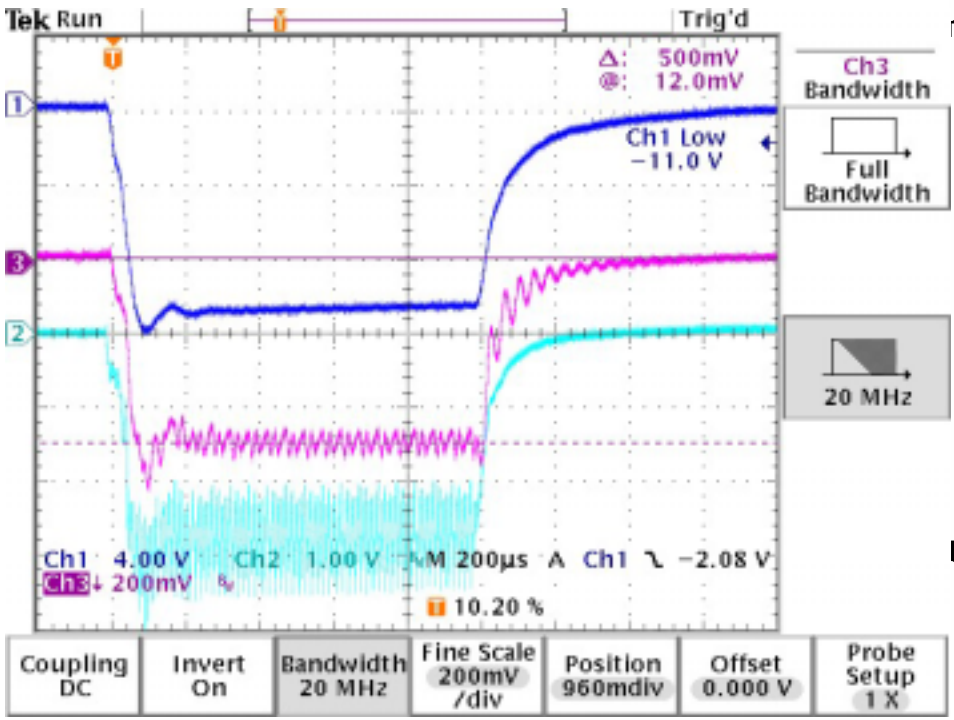
PanelView display – identical to EPICS screens

Control Chassis – controls IGBT gating and fast signals

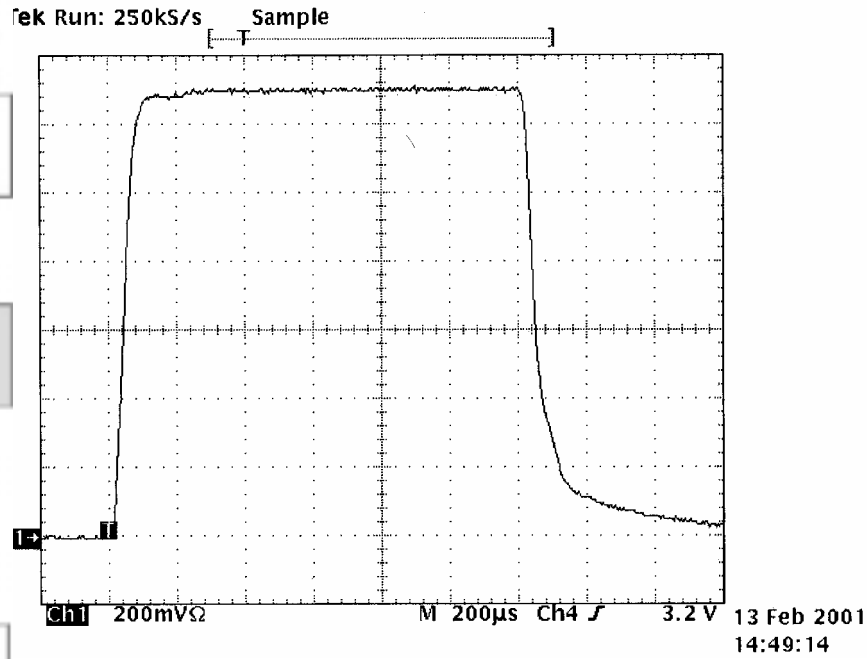
Interlock Chassis – manual reset of personnel faults and keyed

PLC Chassis

Demonstrated Output Waveforms



1st –ORNL pulse



1st 80 kV pulse w/ feedback

HVCM Hazards – all mitigated!

- Electrical – up to 150 kV pulsed, 1500 V dc
- Potential explosive energy release – from capacitors
- Thermal – Heating of IGBTs, other components under oil
- Insulating oil – potential for allergic reaction
- Trip / Fall – Cables, grounding bus, etc.
- Water pressure – 120 psi supply line
- Lifting / rigging – maintenance on tank components

Operators' Requirements

- Electrical Worker, LO/TO, CPR required
- OJT, including:
  - Training today
  - Demonstration of operations competency
- Emergency shut down procedures
- Maintenance personnel require additional OJT training

EMERGENCY PROCEDURES

- EVACUATE AREA IMMEDIATELY AND CALL 574-6606!

- IF POSSIBLE AND NO THREAT TO LIFE:
  - Push “EMERGENCY OFF” button on the front of the control rack OR SCRAM button in aisleway
  - Remove power feed to the system by opening the main circuit breaker
  - Remove 2100 V AC power from SCR unit by remotely opening switchgear

EMERGENCY NOTIFICATION LIST

- David Anderson Office: 241-7518 Cell: 300-5346
- Jim Hicks Office: 574-3180 Cell: 405-9689
- Ray Fuja Office: 241-6133 Cell: 405-6450

•In event of electrical accident:
  - •Div/Group ESO: David Anderson Office: 241-7518
    Home: 463-6746 Cell: 300-5346
  - •Division Office: Norbert Holtkamp 241-6945

•Oil or water spill:
  - •Facility Manager

•ASD Safety Representative: Sam McKenzie 241-8054

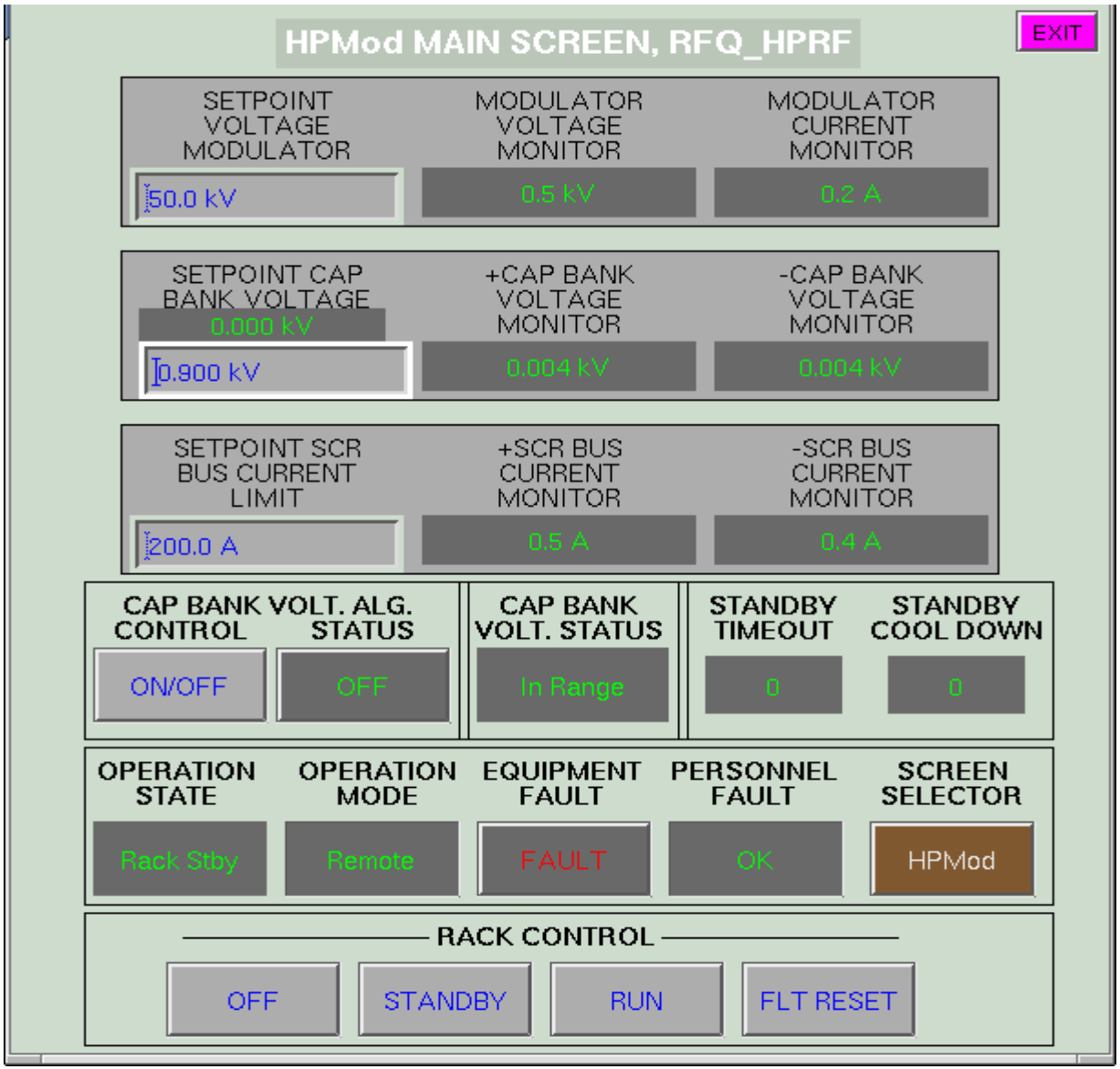
JHA / SOP Important Points

- Previous slides
- Authorized Worker Acknowledgement and Verification of HCP Review
- Modulator Start-Up Procedure Checklist
- Modulator Shutdown Procedure Checklist

- All Operators, Operator Support Personnel, and Maintenance Personnel must be listed.

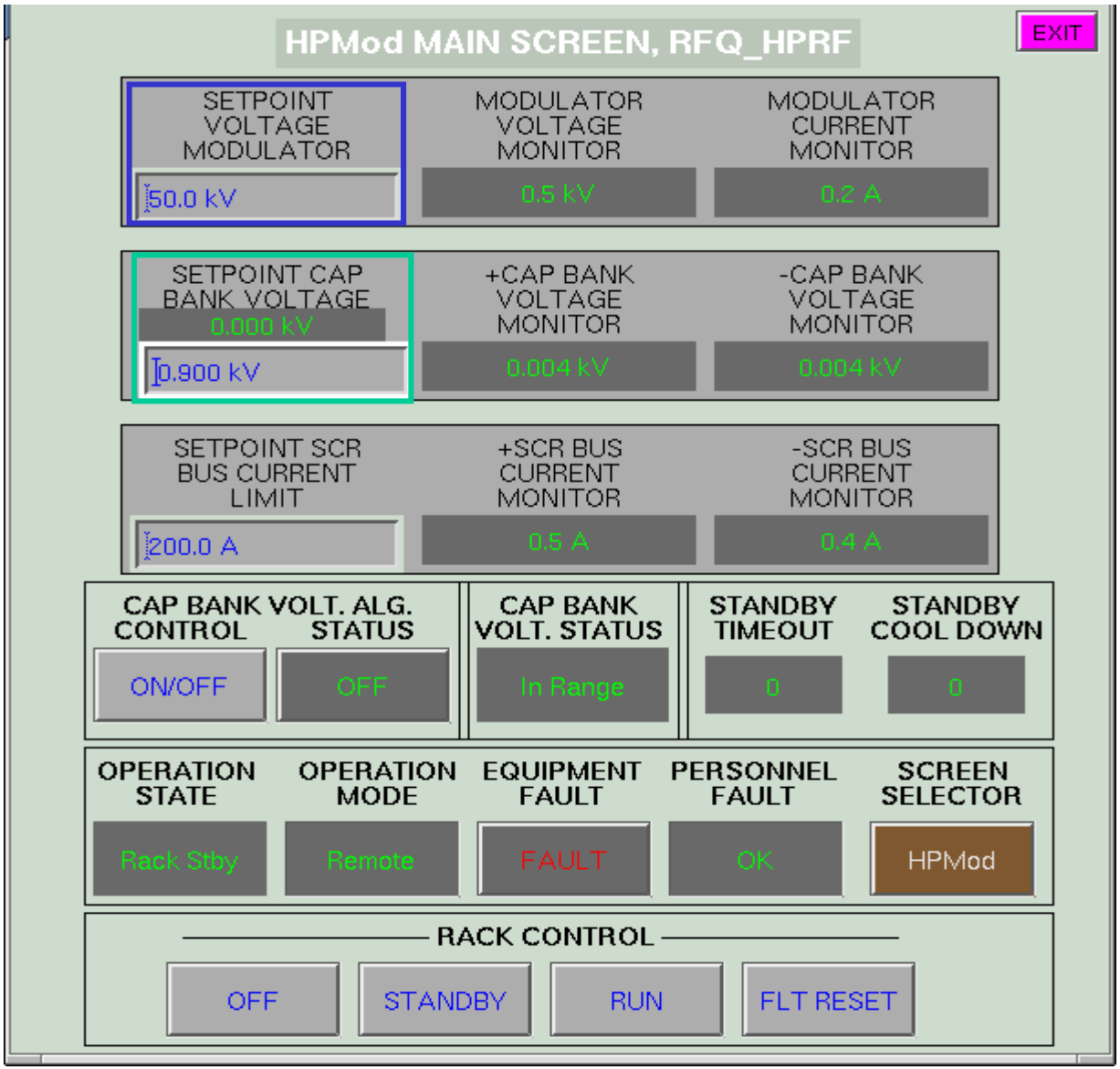
- **Minimum of 2 people required for operation, checkout, testing, or maintenance of HVCM!**

Operating HVCM – All Screens



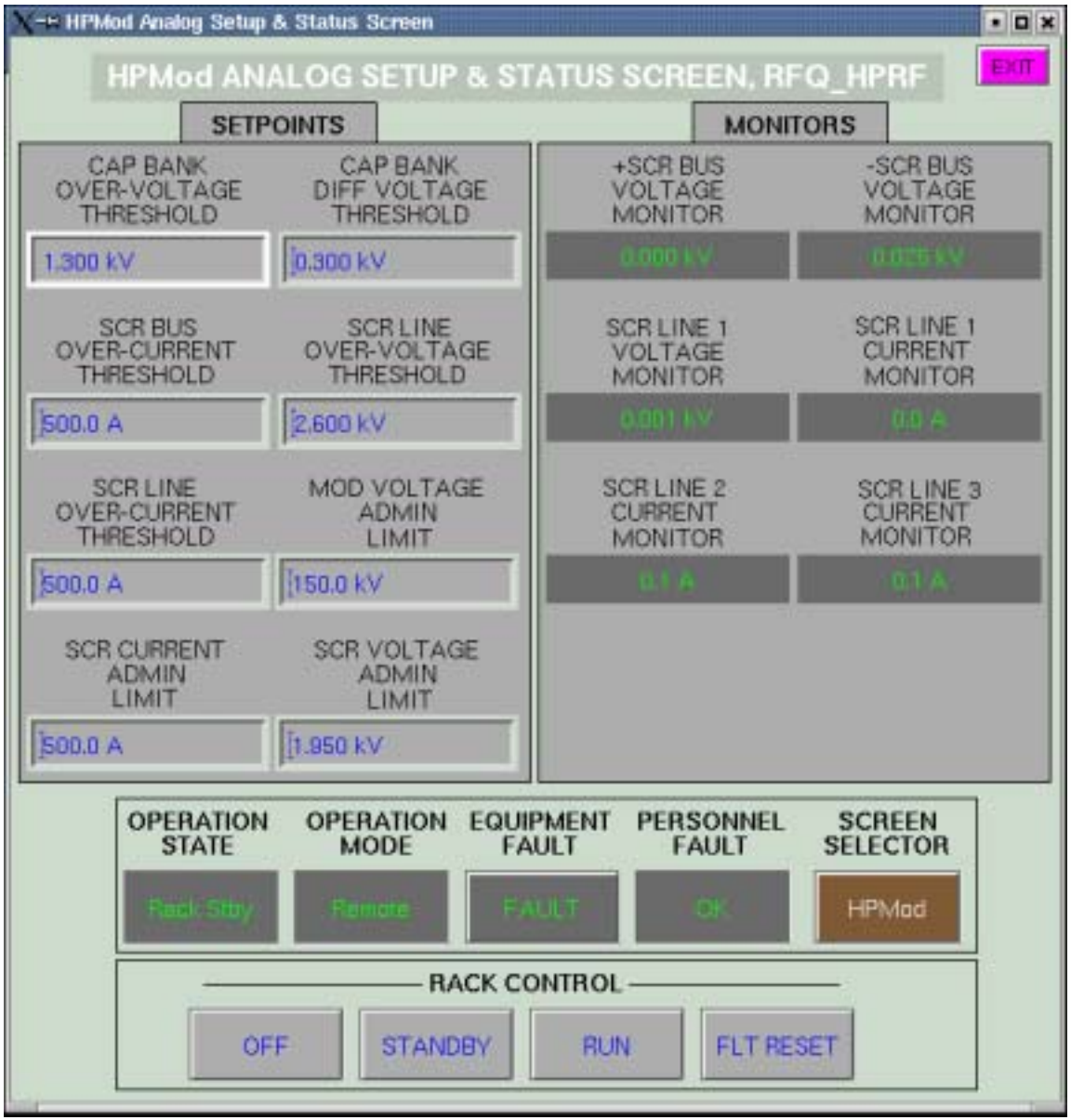
- Oper. State
  - Off
  - Standby
  - Run
- Oper. Mode
- Equip. Fault
  - Reset with Flt Reset button
- Personnel Fault
  - Reset locally only
- Screen Selector

Operating HVCM – Main Screen



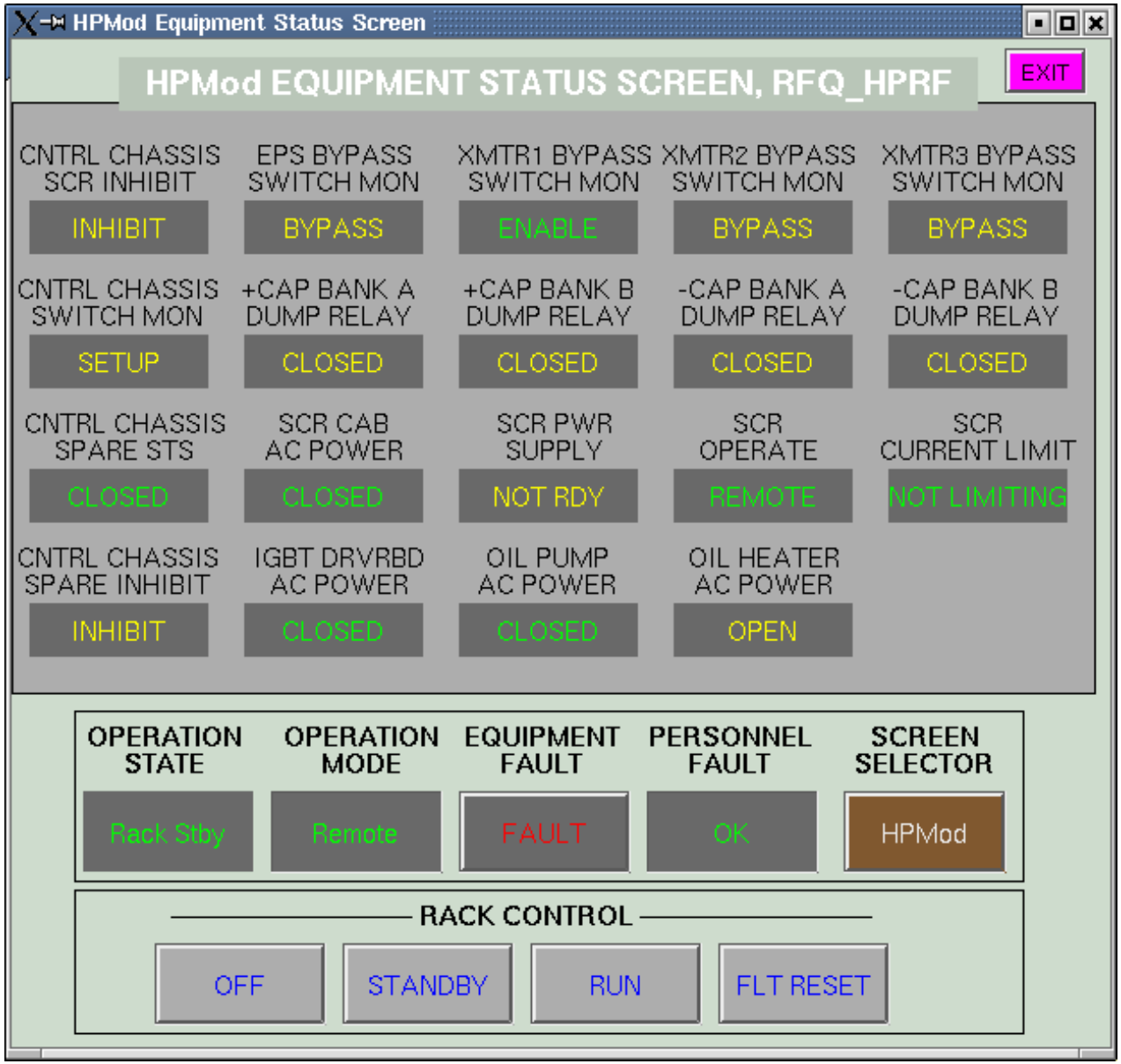
- Setpoints in green open-loop, blue closed-loop
- Cap Bank V Algorithm for future use
- SCR Bus Current and Cap Bank V (X2) determine average power

Operating HVCM – Analog Setup



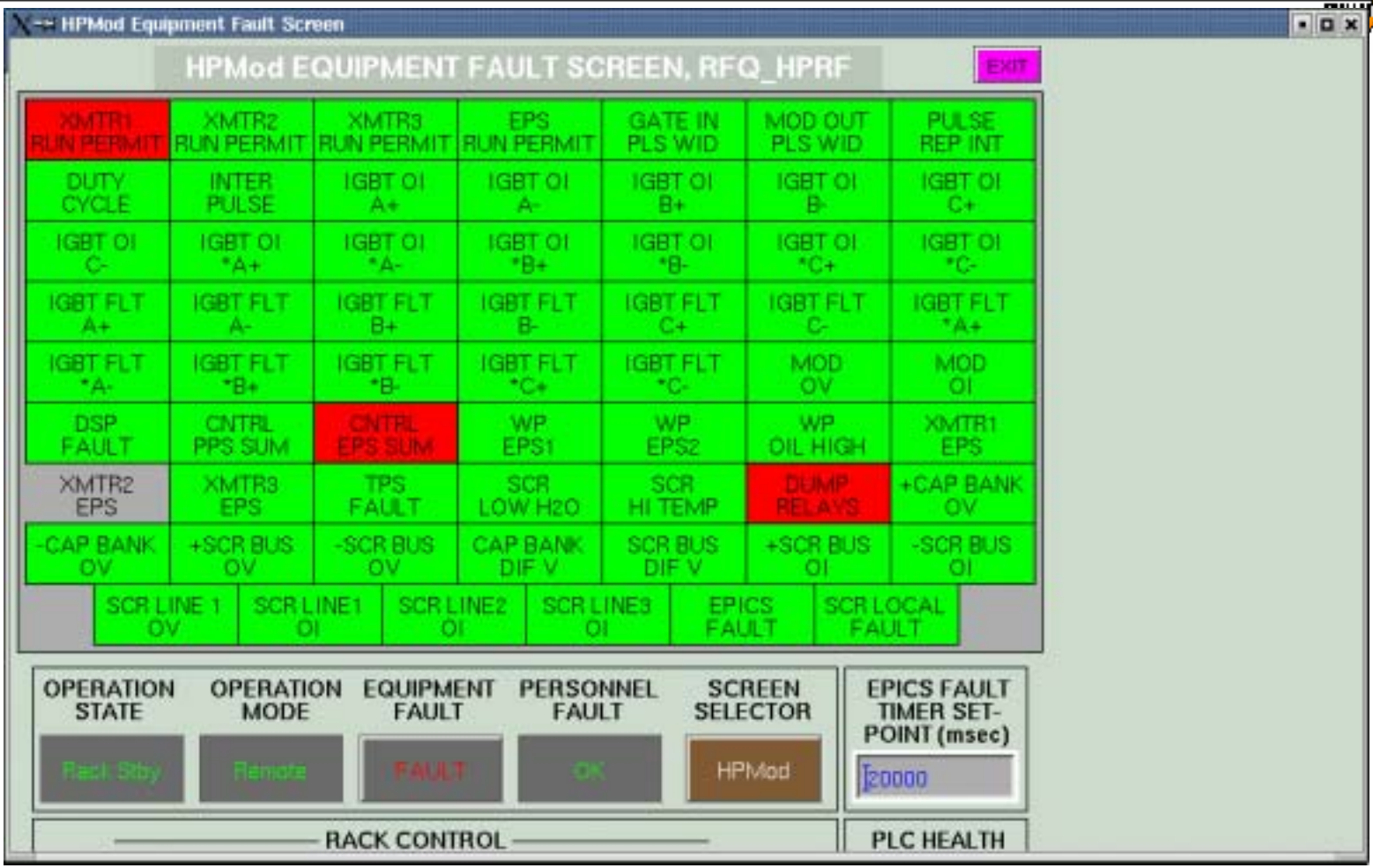
- Controls for administrative limits – must be set locally!
- Monitors may be useful for troubleshooting

Operating HVCM – Equipment Status



- Verifies if bypasses are enabled
- Verifies Dump Relay status
- Verifies SCR and power distribution status

Operating HVCM – Equipment Fault



- Most useful screen for troubleshooting
- All green (except Dump Relays) during operation
- Corresponds to troubleshooting table

Operating HVCM Fault Troubleshooting Table

•XMTRn RUN PERMIT – Transmitter crowbarred HVCM, check transmitter
•EPS RUN PERMIT – MPS inhibited HVCM, check MPS log
•GATE IN PLS WID – Incoming gate pulse width >1.5 ms, check timing module or setting
•MOD OUT PLS WID – Voltage readback pulse width too wide, check cable connection and/or klystron connection
•PULSE REP INT – Rep rate >60 Hz, check timing module or setting
•DUTY CYCLE – Duty cycle > setpoint, check timing module or setting
•INTER PULSE – Voltage present on readback outside of gate pulse, check cable connection and/or klystron connection
•IGBT OI n+/- – IGBT currents exceed threshold setpoint. If fault reoccurring, contact HVCM tech. or engineer
•MOD OV – Modulator voltage exceeds setpoint in closed loop mode, adjust on Main Screen or possible fault due to klystron not conducting current
•MOD OI – Modulator current exceeds setpoint, adjust on Analog Status & Setup Screen (requires HVCM tech. or engineer) or fault due to klystron or internal arcing.
•DSP FAULT – DSP in control chassis faulted, contact HVCM tech. or engineer
•CNTRL PPS SUM – PPS fault, requires local reset (consult Personnel Fault Screen)
•CNTRL EPS SUM – Equipment fault, reset remotely (consult Equipment Fault Screen)
•WP EPSn – Water panel ‘auxiliary fault, presently hardwired.

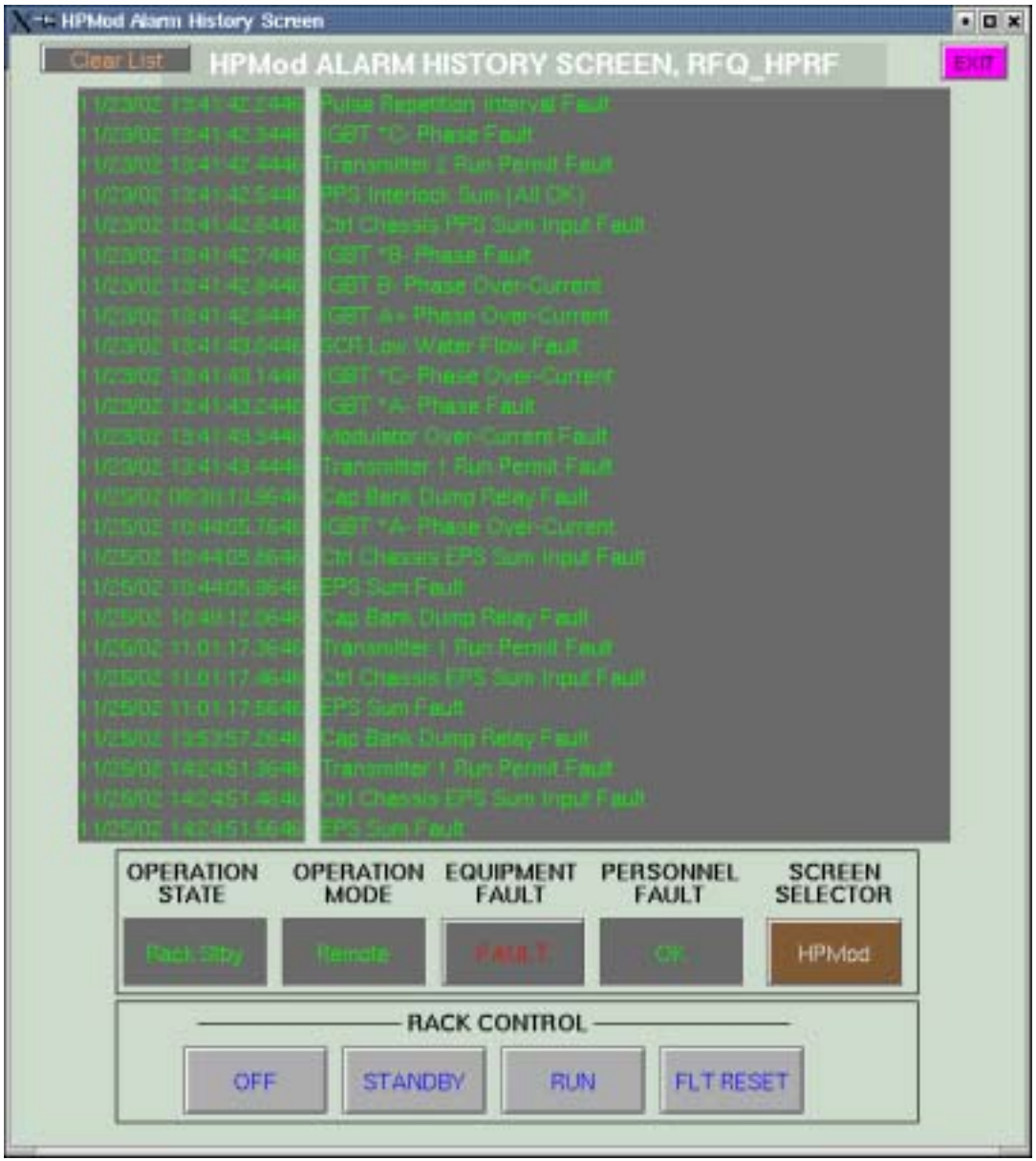
Operating HVCM Fault Troubleshooting Table

•WP OIL HIGH – Oil level too high, probably due to heating. Contact HVCM tech. or engineer
•XMTRn EPS – Transmitter equipment protection fault, check transmitter screen
•TPS FAULT – Target protection system fault (presently not installed)
•SCR LOW H2O – Low water flow in SCR unit, check valves and call HVCM tech. or engineer if doesn't clear
•SCR HI TEMP – Water return temperature too high, check supply temperature and call HVCM tech. or engineer if fault doesn't clear
•DUMP RELAYS – Dump relays status
•+/-CAP BANK OV – Voltage exceeds setpoint, adjust on Main Screen
•+/-SCR BUS OV – Voltage exceeds setpoint, adjust on Analog Status & Setup Screen
•CAP BANK DIF V – Voltage imbalance. Try again and contact HVCM tech. or engineer if fault doesn't clear
•SCR BUS DIF V – ditto above
•+/-SCR OI – SCR DC current too high. Adjust setting on Analog Status & Setup Screen
•SCR LINE n OV – SCR AC current too high. Adjust setting on Analog Status & Setup Screen
•EPICS FAULT – self-explanatory
•SCR LOCAL FAULT – Fault in SCR control head. Reset, try again, and contact HVCM tech. or engineer if fault doesn't clear

Operating HVCM – Personnel Protect Fault

- Faults jeopardizing personnel safety
- Must be reset locally at Interlock Chassis!

Operating HVCM – Alarm History



- Useful for troubleshooting
- Logs all faults in order